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**Research article**

# The impacts of 3D printing on traditional Chinese silk making: Exploring challenges, opportunities and balance of cultural preservation

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## Abstract

This study critically investigates the opportunities and challenges of applying 3D printing technology in traditional Chinese silk-making, addressing a notable gap in existing literature which has received inadequate research attention. This is achieved through exploring the types of new technologies adopted in traditional Chinese silk production, evaluating the impact of 3D printing, investigating barriers to its adoption and how traditional and modern techniques can be balanced for cultural preservation. This study collected qualitative data via 11 semi-structured interviews with professionals working in silk production plants in Hangzhou, China, utilising a purposive sampling strategy to allow in-depth insights into the current technological practices and perceptions of 3D printing within the targeted Chinese silk production industry. Research findings revealed extensive adoption of modern technologies in silk production including automated machines, computerised and AI-driven tools, 3D printing, digital inventory systems, robotics, virtual reality for design, inspection and quality control systems, and sustainable technologies, aligning with existing literature on efficiency and quality improvements from automation and digital tools but extended it by focusing on traditional Chinese silk production. Moreover, 3D printing emerged as a transformative tool that enhances the functionality and customisation capabilities of silk fabrics, offering unprecedented customisation opportunities and significant environmental benefits such as reducing material waste and minimising the use of water and chemicals. This study contextualises these benefits within traditional Chinese silk-making, demonstrating that 3D printing supports sustainability goals while enhancing production efficiency. However, significant barriers exist such as high startup and maintenance costs, lack of technical expertise, a steep learning curve and cultural preservation concerns. These factors deter wider adoption, emphasising the need for substantial investment in continuous training and support. Successful integration of modern technologies with traditional methods was achieved through selective adoption and collaboration with traditional artisans, maintaining authenticity and promoting cultural significance. The study's hypotheses were supported, showing that 3D printing enhances functionality, usefulness, efficiency and environmental sustainability in silk production, although significant barriers remain, with appropriate strategies these challenges can be mitigated.

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## 1. Introduction

The integration of 3D printing technologies in traditional Chinese silk making represents a transformative connection between heritage and innovation in the fashion industry, as a technology that facilitates precise control and customisation 3D printing has been extensively explored in various fields including biomedical engineering and materials science (Wang et al., 2019; Mu, Fitzpatrick, & Kaplan, 2020). However, its application within the realm of traditional silk production remains under-researched, particularly regarding its impact on cultural values and from the perspectives of Chinese fashion companies. According to Feng (2020) and Zanier (2020), traditional Chinese silk making possesses rich historical and cultural significance, represent a craft that has been passed down through many generations across 7 millenniums that embodies artisanal skills and deep cultural heritage. Nonetheless, despite its widely recognised historical roots, the silk industry faces a wide range of contemporary challenges including labour intensity, environmental concerns and the external market pressures to remain competitive in global markets (Babu, 2012; Qin & Xiaoming, 2022). Subsequently, as the largest producer of silk across the globe, China contributes to over 70% of the world's silk output that are turned into fashion apparel products (INSERCO, 2024), this research aims to provide valuable insights into how emerging technologies like 3D printing can coexist cultural preservation for Chinese silk production in the fashion industry.

### 1.1 Research rationale

Despite the notable recognition in recent research that acknowledges the significant advancements that 3D printing technology brings to traditional silk production as well as its challenges (Babu, 2012; Mu et al., 2020; Zanier, 2020), emphasising the need to balance productivity, efficiency and environmental benefits with cultural preservation (Feng, 2020; Qin & Xiaoming, 2022). There is an apparent gap in current literature concerning the application of 3D printing technologies within traditional Chinese silk production when applied towards the fashion industry, as numerous studies have attempted to explore and examine its effects in biomedical engineering applications (Wang et al., 2019; Zhou et al, 2021; Zhang et al., 2021). Therefore, this reveals a clear gap with insufficient research currently on balancing cultural preservation with leveraging 3D printing technology in Chinese silk production for the fashion industry, this study is thus designed to directly address these gaps which will be discussed in more detail in the literature review chapter.

## 1.2 Research aims and objectives

This research aims to critically analyse the opportunities and challenges of applying 3D printing technology in traditional Chinese silk-making. To fulfil this aim, the following research objectives are proposed:

- To explore the range of new technologies adopted within traditional Chinese silk production.
- To evaluate the extent to which 3D printing technology enhances the functionality, perceived usefulness, efficiency gains and reduces environmental impacts of silk fabrics in comparison to traditional Chinese silk production methods.
- To investigate the challenges and barriers to the adoption of 3D printing technology in the Chinese silk fashion industry including high start-up and maintenance costs, lack of technical expertise, perceived difficulty of use and potential loss of traditional cultural values.
- To explore how traditional and modern technology-assisted silk production techniques can be effectively balanced for cultural preservation.

## 2. Literature review

This chapter critically reviews a range of literature within the chosen research scope of balancing traditional with new technologies in fashion production. The first section performs an empirical review of the wider themes on impact of technology on fashion production, followed by its specific effects on traditional crafts and Chinese production. The review then proceeds to the chosen research scope of technology impacts on silk production, specifically on 3D silk prinking on traditional silk production in China where insufficient research studies have been conducted on. Based on this research focus and identified gap, the main themes emerged from 12 key papers are critically discussed as an in-depth summary of these papers is shown in the meta-analysis table in Appendix A. The second part includes a review of theoretical underpinnings from theories and concepts used in relevant studies, aiding the development of a proposed conceptual framework for this research with formulated research questions/ hypotheses.

### 2.1 Impact of technology on fashion production

The application of new technologies in fashion production represents a growing trend in academic literature, receiving extensive research attention that focuses on the use of technologies to enhance sustainability and efficiency in fashion production (Denuwara et al., 2019; Niinimaki et al., 2020). Empirical studies highlight several key technological advancements and their transformative potential that revolutionises the fashion industry including RFID/ RTFS systems and immersive (AR, VR, XR) technologies (Nayak et al., 2022; Mesjar et l., 2023; Shou & Domenech, 2022).

Recent studies have shown that RFID technology significantly enhances sustainability in fashion production by improving inventory management, reducing waste and increasing transparency in supply chains, facilitating environmental sustainability by enabling better stock visibility and reducing the likelihood of overproduction which has long been a critical issue in conventional fashion production (Nayak et al., 2022). Furthermore, Lee (2021, p10) examined the use of RFID technologies with the combination of AI in fashion supply chain production, enabling a sustainable real-time fashion system (RTFS) between actors in the fashion production supply chain as shown in figure 1 below, demonstrating the potentials of integrating AI and RFID technologies to substantially reduce time and costs with precise sampling and tracking capabilities, thereby ensuring securities and personalisation in fashion service delivery.

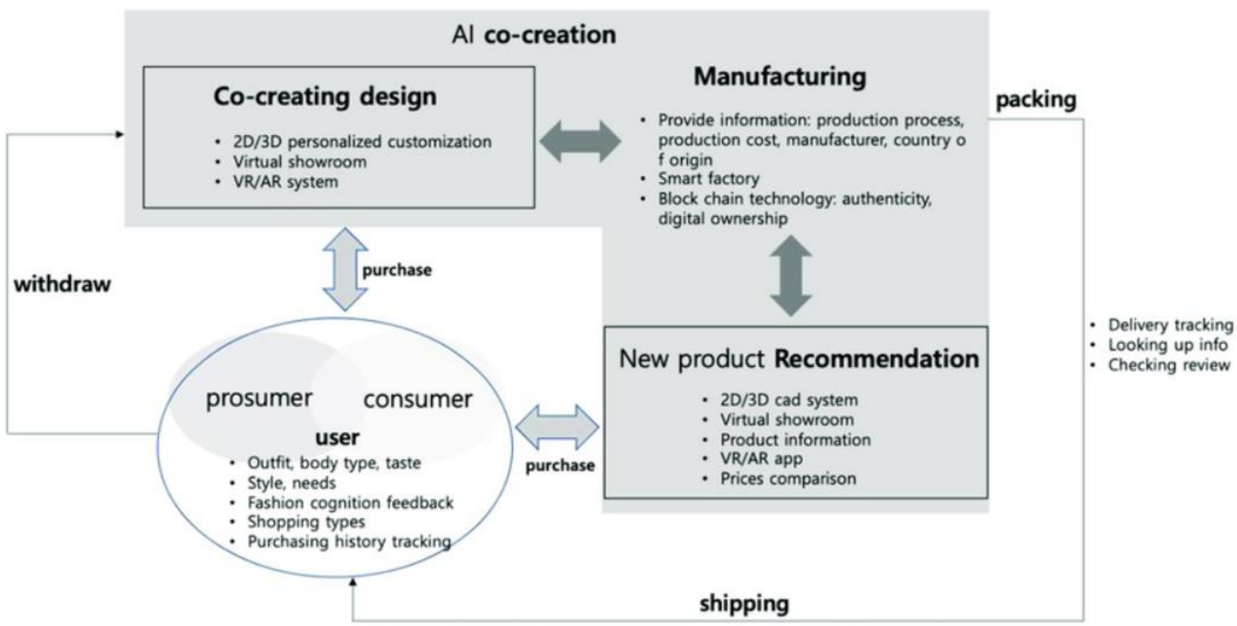


Figure 1: AI integrated RTFS sustainable fashion production support chain (Lee, 2021, p10)

Another key research trend indicates the use of immersive technologies including augmented reality (AR), virtual reality (VR) and extended reality (XR) to transform customer experiences and promoting sustainability in fashion (Silvestri, 2020; Faria et al., 2023). A study by Mesjar et al., (2023) critically examined the transformative potentials of virtual try-on (VT) applications facilitated by AR technologies, finding that it would directly enhance shopping experience satisfaction and reduce return rates that contribute to more sustainable consumption. Furthermore, the combination of VR technologies and the metaverse is found to offer digital fashion innovation that reduces physical production through dematerialisation, allowing designers to freely create virtual prototypes that streamlines fashion design and production processes with elimination of material waste (Sayem, 2022). The application of VR technologies in the fashion metaverse offers an entirely digital space where fashion can be showcased and sold without physical production, as Cobben (2022) argues that this digital fashion innovation revolutionised fashion production by opening avenues for creativity and consumer interaction. Faria & Cunha (2023, p52) identified a range of application of XR technologies in fashion production as summerised in figure 2 below, highlighting the fashion processes where XR can facilitate innovative customer engagement and marketing values, fostering greater recall, recognition and adoption among customers.

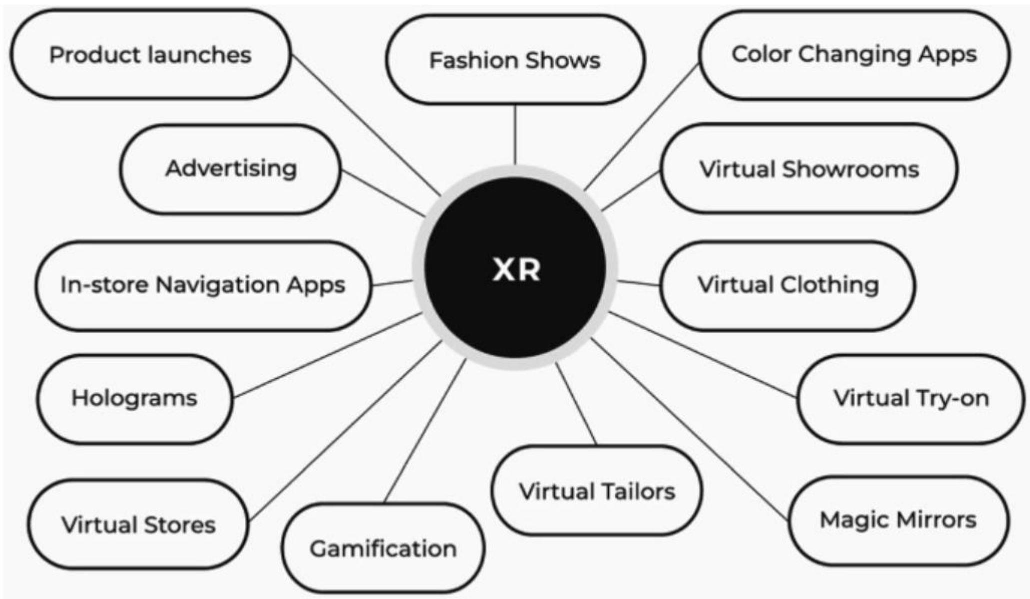


Figure 2: XR application in fashion production (Faria & Cunha, 2023, p52)

## 2.2 Impact of technology on traditional crafts

The integration of technology into traditional crafts has led to significant transformations, providing both opportunities and challenges as advancement of digital tools such as 3D modeling, CAD software and CNC machining have enhanced the precision and scalability in traditional craftsmanship (Bawono et al., 2024; Burke & Sinclair, 2015; Hughes & Sinclair, 2010). Case studies have shown that artisans incorporating these tools achieve improved product quality and production speed with facilitated computer-aiding manufacturing processes in apparel and textile products (Burke & Sinclair, 2015; Gulati & Mathur, 2017). Additionally, Belhi et al., (2017) explored the impact of digital archiving and VR technologies on preserving traditional techniques, finding that it enables the of cultural heritage craft and techniques to be transmitted to future generations. Similarly, VR and AR technological applications are increasingly used in educational settings to teach and promote traditional crafts, aiding in cultural heritage preservation as old cultural crafts can be reconstructed digitally and preserved (Shih et al., 2020). Shih et al (2020) further elaborated on the use of photogrammetry modelling to create 3D models of cultural artefacts and crafts from the Zhongshan road and the artist village in Lukang, Taiwan as shown in figure 3, reconstructing the objects accomplished by intensive cloud computation with clear structural details.

Figure 3: Cultural artefacts and crafts created by 3D photogrammetry modelling (Shih et al., 2020, p7)

Under an economically perspective, technological advancements have significantly impacted local communities involved in traditional crafts by expanding their market reach through e-commerce and online platforms, thus enhancing the livelihoods and social status of traditional craftsmen as shown int Nayak et al.'s (2022) study on Vietnamese traditional craft. Additionally, Sun & Liu's (2022) study on bamboo basketry examined how technology can revitalise traditional craft, addressing the threats of the dwindling number of skilled practitioners who can produce this form of intangible cultural heritage caused by the lack of labour division between design and manufacturing, which deters professional designers from participating in the craft. The use of digital tools including basic over-under structures, automatic 2D to 3D mapping and digital representations of weaving techniques like connecting, wrapping, plaiting and knotting enabled the precise expression of design concepts through digital models, allowing designers to create detailed digital representations of their weaving structures without needing to produce physical samples to attract more designers into this craft (Sun & Liu, 2022). Another research theme points to the promoted sustainable practices in traditional crafts by facilitating the use of environmentally friendly materials and processes in new technologies (Aytekin & Rizvanoglu, 2019). This is particularly evident in the Sri Lankan handloom industry with the implementation of digital tools and platforms that reduce material waste and promote eco-friendly production methods, such as 3D printing using biodegradable materials and laser cutting to minimise fabric waste, thereby contributing to the overall sustainability of traditional crafts (Wanniarachhi et al., 2020).

### 2.2.1 Impact of technology on Chinese fashion production

Empirical literature on the impact of new technologies on Chinese fashion production often adopts a marketing and economic approach to examine the rise of e-commerce and online platforms like Alibaba and JD.com which has dramatically expanded market reach for Chinese fashion brands (Chan et al., 2018; Jiang et al., 2022). According to Chan et al., (2018), these platforms have facilitated increased sales and access to a broader customer base, significantly boosting the economic performance of many brands. Furthermore, the advancement of big data analytics technology has allowed fashion brands and manufacturers to tailor their marketing and production strategies to consumer preferences, enhancing customer engagement and loyalty with increased market precision (Silva et a., 2020). A recent research trend has emerged on the development of additive manufacturing technologies which is found to have significantly impacted sustainable practices, labour and production processes in the Chinese fashion industry. Defined by Gibson et al., (2021) as an emerging technology that manufactures objects directly from digital models through an additive process one layer at a time until the final product is complete, more efficient and sustainable production practices are enabled. Khajavi (2021) highlighted the use of addictive manufacturing with biodegradable materials to reduce wastage and environmental impacts, discussing its transformative potentials for fast fashion firms due to its rapid prototyping capability as well as for high-end fashion brands for its facilitated freedom in customisation.

Furthermore, there is an apparent rise in the adoption of automation technologies including robotics and AI-driven machinery in Chinese fashion production, as Wang & Su (2021) found that the facilitated automation contributes to reduced labour costs and increased production spend, enabling manufacturers to meet high market demands more efficiently. The use of robotics in the Chinese shoe making industry has resulted in faster turnaround times and reduced reliance on manual labour, allowing for more consistent product quality and quicker adaptation to market trends as found in Yvone & Cixin's (2021) study. However, the adoption of new technologies in Chinese fashion production is also recognised to pose substantial challenges, as a study conducted by Majumdat et al., (2021) identified high implementation costs and technical skill gaps as significant barriers, particularly for small and medium-sized textile and clothing enterprises (SMEs). It is found that smaller companies often struggle to afford the upfront investment in advanced machinery and the associated costs of training employees to operate and maintain these systems, whereby the rapid pace of technological change can also outstrip the ability of these smaller companies to keep up thus exacerbating the apparent skill gap especially in upcycled fashion products in China (Yoo et al., 2021).

## 2.3 Traditional silk production methods and challenges

Traditional silk production methods and processes dates back hundreds of years ago and is often characterised as a labour-intensive process that requires expertise craftsmanship according to Babu (2012). Moreover, Babu (2012) provided a comprehensive overview of these traditional silk production methods and raised the concerns over apparent challenges that have persisted over time due to its complex process that includes a range of craftsmanship demanded skills such as sericulture, reeling and weaving. Similarly, Mu et al., (2020) also reinforced this argument by suggesting that traditional silk production methods demand specialised skills and substantial labour, whereby its labour-intensive characteristic is argued to be the main challenge due to coupled vulnerability to uncontrollable changes in labour availability and costs. Furthermore, Babu (2012) highlighted the ecological challenges and difficulties to managing and maintaining silkworm ecosystems, whereby potential diseases or health issues would pose persistent threats to silk yield and quality of silk produced. A key theme on the challenges of traditional silk production is associated to its drastic environmental impacts, as the generation of waste in forms of sericin and wastewater require effective management strategies to mitigate subsequent environmental degradation impacts (Babu, 2012).

Additionally, Mu et al., (2020) argues that the rising expectations for sustainable practices in recent years have further complicated the challenging landscape of traditional silk production impacts on the environment, as increasingly health and environmental conscious modern consumers and regulators are demanding eco-friendly production methods with the goal of alleviating environmental degradation. Consequently, the silk producers have embraced the development and application of new technologies to addresses these challenges, striving to reduce waste and improve the efficiency of silk production but is criticised by Babu (2012) to be still of nascent nature that holds apparent scalability and cost effectiveness challenges. Similarly, Qin & Xiaoming's (2022) focus of silk production challenges in China highlighted the industry's cultural and economic significance, arguing that traditional silk production remains deeply intertwined with local heritage and identity that the Chinese government has attempted to encourage innovation in addressing traditional silk production challenges whilst attempting to preserve traditional artisan methods. This raises the apparent challenge to balancing innovation with heritage preservation, ensuring that the cultural significance of silk production is not lost in the face of technological advancement and remains a relatively under-researched gap where inadequate studies exist, thus this study will contribute to the gap by exploring how Chinese silk producers are balancing both technological innovation and traditional practices.

### 2.3.1 Advanced silk processing techniques and technologies

Due to rapid technological advancement in recent decades, advanced silk processing techniques have been developed and is revolutionised the application and production processes of silk beyond traditional methods and use (Agostinacchio et al., 2024). According to Mu et al., (2020), directed hierarchical molecular assembly methods has been adopted to create silk-based materials with enhanced mechanical properties and biocompatibility, enabling the fabrication of highly complex structures that are suitable for advanced biomedical applications such as tissue engineering and regenerative medicine beyond conventional fashion use. Moreover, the advanced developments of 3D printing technologies have been applied in silk production, as Wang et al.'s (2019) study highlighted the versatility of silk fibroin produced by 3D printing technologies, making it feasibility as a bioink to create biocompatible and mechanically robust structures, addressing its traditional challenges in environmental impacts ad dependency on silkworm conditions identified by Babu (2012). Moreover, Wang et al., (2019) found that 3D printed silk fibroins to be particularly beneficial in drug delivery systems, as it is easily stored and provides robust characteristics that can be used for tissue scaffolds and would dressings, arguing that 3D printing technologies enable the leverage of silk's natural properties alongside exercising precise control of the materials architecture, opening new possibilities in a range of different fields and applications.

Zhou et al., (2018) contributed to this discourse by examining other types of advanced silk processing techniques in the fields of electrospinning and microfabrication, finding that the produced silk materials would enhance mechanical properties, biocompatibility and the overall functionality compared to traditional silkworm produced silk. According to Zhou et al., (2018), electrospinning technologies enables high precision in silk fibre production to nanoscale diameters, enhancing the surface area which can aid biomedical applications, alternatively, microfabrication technologies facilities customised patterning of silk materials which enhances its usage in bioelectronics. Additionally, Agostinacchio et al.'s (2024) study successfully produced silk fibroin inks through a double crosslinking process that enhances both the mechanical properties and stability of printed structures, representing a significant milestone in 3D printing technologies that has aided its application in complex tissue engineering and regenerative medicine practices. Nonetheless, the aforementioned advanced silk processing techniques shares the common theme of its application in complex biomedical applications, illustrating an apparent research gap where there exists a minimal research focus on how 3D printing impacts the fashion industry, which remains a key industry that consumes the highest volume of silk.

### 2.3.2 Historical context and technological advancement of silk production in China

According to Zanier's (2020) systematic historical review of the silk industry's origins in China and its evolution across the silk road, providing historical narrative insights on the silk industry's impact on China's cultural heritage and economic importance in trades between the East and the West. Moreover, Zanier (2020) further elaborated on the evolution of silk production techniques throughout China's ancient history, ranging from the earliest technological innovations in improved reeling techniques during the neolithic – Yangshao culture $4^{th}$ millennium BC era to the development of electric powered silk weaving machinery in the $20^{th}$ century. Feng (2020) also examined the evolution of silk production technologies and their significance along the silk road, highlighting the role of technological advancements in facilitating the long-distance trade of silk that was highly valued for its quality and craftsmanship by the West, suggesting that earlier technological innovations in silk production enhanced the durability and aesthetic appeal of silk fabric which them more desirable in international markets.

In more contemporary context, technological advancements has continued to reshape China's silk industry, as Hui (2010) critically examined China's silk production and trade structure between the 1980s and 2000s, highlighting the influence of economic reforms and increasing globalisation that has resulted in the development of automated reeling machines and computerised looms, significantly increasing production efficiency and reduced labour costs in comparison to the traditionally labour intensive efforts required in silk production. According to Hui (2010), these technological advancements were vital for Chinese silk producers to remain competitive in the global market, despite rising labour costs and environmental regulations due to the increasingly stringent controls by the Chinese government upon its economic reform in 1978. Another study by Zhou et al., (2018) emphasised on the advancement of electrospinning technologies as a method to produce silk fibres with nanoscale diameters, arguing that the facilitated high strength and flexibility to have created unique competitive advantages of Chinese silk producers, whereby complex and detailed patterns that were previously challenging to produce can now be achieved with precision, highlighting the importance of continuous technological innovation for China's silk industry to compete on the global stage.

### 2.3.3 Traditional cultural values impacted by 3D printing and new technologies in Chinese silk production

Another key theme amongst empirical studies highlights the impact of 3D printing in silk production on traditional cultural values, representing two opposing school of thoughts that emphasis on the opportunities and the challenges in balancing innovation with cultural heritage. Wang et al.'s (2019) study on the biocompatible and mechanical robust potentials of 3D printing silk fibroin highlight its potential in opening new markets, especially in biomedical applications in areas of tissue scaffolds and drug delivery systems. However, the facilitated feasibility of using 3D printed silk fibroin also raises concerns over the preservation of cultural practices and values associated to the traditional craft of silk production that is symbolical of the industry's seven millennium long existence (Wang et al., 2019). Another major challenge identified by Wang et al., (2019) relates to the economic pressures caused to the traditional handcrafting silk production techniques. Despite the need for high initial and maintenance costs of specialised equipment and materials that presents apparent technical and financial barriers for Chinese silk producers, the potential long term economic benefits could encourage the shift towards automated production processes, subsequently eroding the artisanal skills that are a cornerstone of cultural heritage in China's silk production.

According to Perez et al's, (2020) interdisciplinary research study, 3D printing technologies enable the digitalisation and preservation of cultural heritage which is particularly beneficial for educational purposes, arguing that these technologies could help to replicate historical silk fabrics that are difficult to produce or have been lost in history. The interdisciplinary method proposed by Perez et al. (2020) was found to substantially contribute to preserving historical textiles and providing valuable educational tools, which would help institutions like schools and museums to educate via almost close to perfect replicas and through interactive virtual representation methods. Agostinacchio et al. (2024) further exemplified on the impacts of 3D printing technologies from a market perspective, arguing that whilst incorporation of this technology into silk production would directly benefit customer engagement and satisfy their increasingly demanding expectations, the loss of artisanal value of silk products produced with automated machines would thus undermine the perceived authenticity and traditional cultural values that has long been embedded into the craft of silk making. Moreover, studies by Feng (2020) and Zanier (2020) also reinforced the idea of maintaining traditional techniques in silk production with emphasis on its long history along the silk road, positing that the adoption of modern technologies would require strategic cultural implications with the goal to preserve the heritage associated with silk production. This is reinforced by Zanier's (2020) claim that the cultural heritage of silk production does not rest in the final product but also throughout the entire production process, embodying key technical and tacit knowledge that has been passed down through generations of artisan Chinese silk producers.

In summary. empirical research points to the consensus that there is strong recognition over the advancement of technologies such as 3D printing on traditional silk production, however, apparent challenges are also acknowledged and the need to maintain a strategic balance between productivity, efficiency and environmental gains with cultural preservation is needed. Moreover, despite numerous studies dedicated to exploring the effects of 3D printing on traditional silk production in China, these researches have been predominantly centred around biomedical engineering applications, representing a clear gap where there is insufficient knowledge on the impacts of 3D printing on silk production in the fashion industry. Additionally, the lack of studies on how cultural preservation can be balanced with the leverage of 3D printing technology in Chinese silk production for fashion present another research gap for this study to contribute to.

## 2.4 Theoretical review

This section reviews the theoretical underpinnings of the afore review empirical studies, identifying relevant theoretical support that grounds the principle of this study and shapes the proposed conceptual framework.

### 2.4.1 Diffusion of innovations theory (DOI)

The DOI theory was originally developed by Rogers (1962) to provide a comprehensive framework for understanding how new technologies are spread and adopted within a social system, identifying key factors such as innovation characteristics, communication channels, time and social systems to have direct influence on the adoption of new technologies. This theory has been widely adopted amongst empirical studies for analysing and understanding how new technologies can gain acceptance amongst organisations, as evidential in Babu's (2012) historical overview where the spread and acceptance of advanced processing technologies are explored within various social settings. Additionally, Mu et al.'s (2020) study draws upon similar theoretical underpinnings by recognising that traditional silk production methods have altered the perception of adopting new, innovative silk production technologies with increased levels of acceptance, positing the perceived risks and challenges of non-adoption against the potential gains of adoption to determine its adoption in biomedical applications. Moreover, Qin & Xiaoming's (2022) study also aligned to the theoretical underpinnings of the DOI by analysing the development of China's modern silk industry and how technological advancements have played a key role in its evolution, relating external environmental factors such as government policies and market dynamics to have influenced the diffusion of advanced silk production technologies.

### 2.4.2 Technology acceptance model (TAM)

The TAM model was introduced by Davis (1989), originally focusing on how the perceived usefulness and ease of use of certain technologies would serve as primary determinants of technology adoption, this model was latter further expanded to incorporate other technological, organisational and environmental factors due to the increasing dynamics of technologies and the complexity of their applications. The TAM model offers valuable insights on how technologies are perceived by industry professionals and from the perspective of consumers, providing a multi-level perspective approach to understanding the factors behind adopting new technologies or causes of rejection. This is evidential in Wang et al.'s (2019) study where the TAM model was employed to evaluate the feasibility and practicality of using silk fibroin as a bioink for 3D prinking, assessing key areas such as perceived usefulness and the perceived ease of use of adopting this technology to create biocompatible structures. Additionally, Zhou et al.'s (2018) study also aligned the key components of the TAM model to explore how perceived usefulness of advanced manufacturing techniques for silk materials affected its adoption, particularly in relation to its enhanced mechanical properties and improved functionalities. Agostinacchio et al (2024) further reinforced this by utilising the TAM model components in assessing the development of silk fibroin-based inks for 3D printing, also drawing upon the perceived ease of use and the practical benefits as key determinants of adopting silk fibroins under a double crosslinking process for biomedical applications. Nonetheless, the TAM model is widely applied when exploring the application of new technologies in fashion, as shown in the studies of Pookulangara et al., 2021 and Saha (2023).

### 2.4.3 Proposed conceptual framework

In consideration of the identified key themes in empirical studies and theoretical underpinnings, the following conceptual framework is proposed for this study as shown in figure 4.

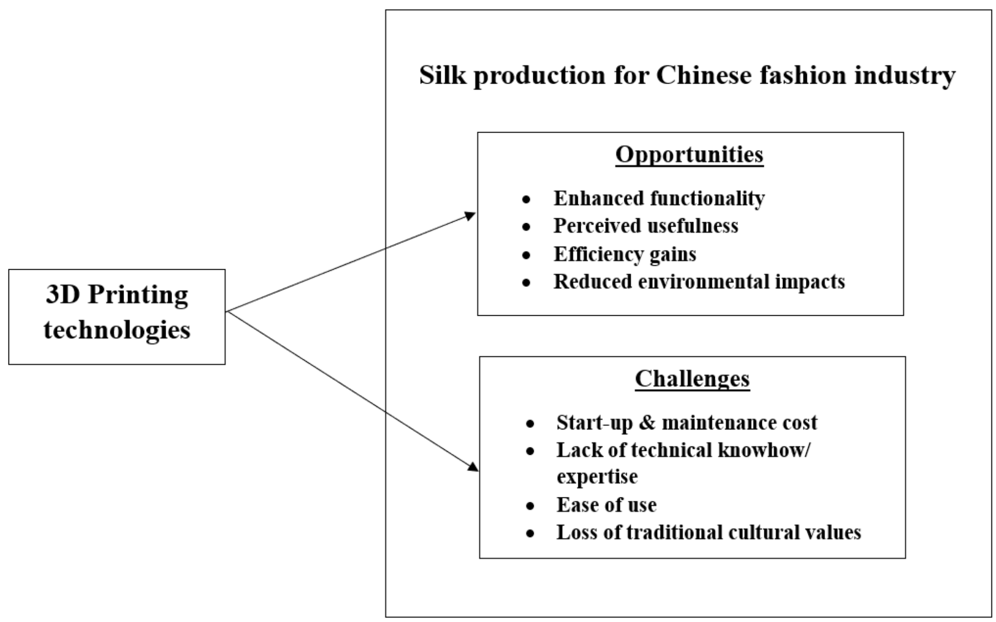


Figure 4: Conceptual framework

## 2.5 Research hypotheses

Given the chosen research design and scope to contribute to the identified research gap where inadequate studies have been dedicated to explore the opportunities and challenges of 3D printing technologies in silk production for the Chinese fashion industry, the following research hypotheses are triangulated with empirical literature knowledge when applied to other sectors and applications.

**Opportunities based hypothesis:**

- The application of 3D printing technology enhances the functionality of produced silk fabrics, increase perceived usefulness, boost efficiency gains and reduce environmental impacts compared to traditional Chinese silk production methods.

**Challenges based hypothesis:**

- The challenges and barriers such as high start-up and maintenance costs, lack of technical knowhow and expertise, perceived difficulty of use and potential loss of traditional cultural values hinders the adoption of 3D printing technology in the Chinese silk fashion industry.

## 3. Methodology

This chapter presents the methodological design for this study, justifying the section of tools and methods across various stages of the entire research process. This chapter is structured in accordance to Saunders et al.'s (2009) research onion framework as modified in figure 5 below, beginning with an analysis of the chosen research philosophical stance, followed by the research approach, strategies, choices, time horizons and sampling methods in data collection. Ethical considerations and potential limitations are also discussed in relation to how they were addressed.

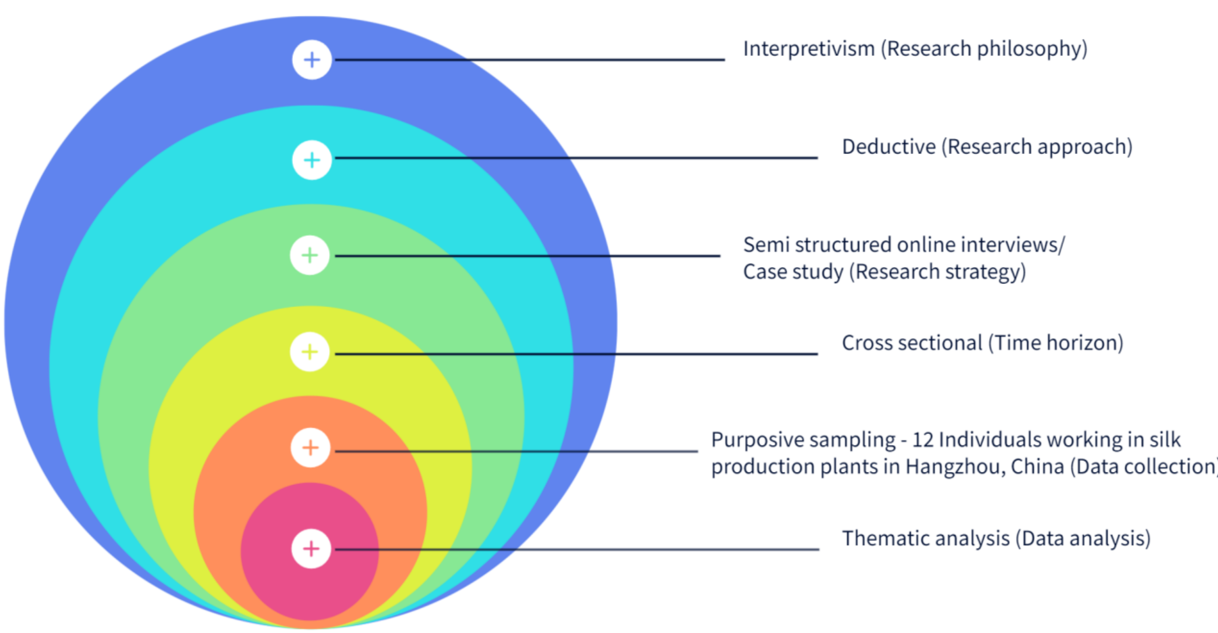

Figure 5: Research onion framework

### 3.1 Research philosophy

According to Bryman (2016), the philosophy of a research governs the ways in which data about a phenomenon should be gathered, analysed and utilised, directly influencing how the perception of knowledge and reality is created. For this study, an interpretivism philosophy is adopted, cohering to the epistemological stance where meanings and experiences of individuals within their social contexts are valued and emphasised (Alharahsheh & Pius, 2020). An interpretivism philosophy is particularly suitable when exploring attitudes as it allows for an in-depth exploration based on specific value-systems that could differ between individuals, echoing Bryman's (2016) discussion of interpretivism philosophy values that it's fundamentally concerned with the subjective interpretation of social phenomena, suggesting that knowledge is constructed through the interactions and interpretations of individual. Subsequently, this allows for a deep exploration of how industry professionals perceive and respond to technological changes facilitated by 3D printing technologies. Moreover, the justification for using interpretivism in this context also lies in its ability to uncover the diverse and multifaceted nature of human experiences as suggested by Alharahsheh & Pius (2020). In contrast to positivism which seeks to identify generalisable laws through objective observation and quantification, interpretivism prioritises the understanding of subjective experiences and meanings that individuals attach to their actions and interactions, this is particularly beneficial when considering the chosen sampling region context of silk production in Hangzhou, where cultural, historical and social factors significantly influence how new technologies are perceived and adopted.

### 3.2 Research approach

This research adopts a qualitative approach and employs a deductive (top-down) approach to generate rich, detailed understandings of the impacts of 3D printing application in traditional silk production for the Chinese fashion industry. According to Thomas (2006), a deductive approach enables the research to critically investigate relevant academic knowledge already existed in empirical studies, forming strong foundation to support the design and theoretical underpinnings of a study. Furthermore, this facilitated academic rigour enables the formulation of proven hypotheses towards a new chosen research context (Thomas, 2006), whereby this study performs this in chapter two to identify empirical literature themes, existing theories and formulates on the identified research gap of the Chinese fashion industry where inadequate studies exist. This approach is well-suited for examining how established theories on technological adoption and cultural preservation apply to the specific context of the Chinese silk industry in systematic manner that compressively explores the anticipated impacts of 3D printing technology on traditional silk production. Additionally, the qualitative nature of this research is essential for capturing the complex, in-depth details of how 3D printing is applied into this culturally significant industry, focusing on the varied experiences of silk industry and fashion professionals that represents a complex cultural practice deeply embedded in social norms and values. A qualitative approach would thus allow the researcher to gather rich, detailed data through methods such as in-depth interviews and participant observations (Creswell, 2013), providing research relevant qualitative insights into how industry professionals perceive and respond to 3D printing technology where quantitative data might fail to capture.

### 3.3 Research strategy of enquiry (interviews)

The research strategy of enquiry for this research is semi-structured online interviews with individuals working in silk production plants in Hangzhou, China. Semi-structured interviews are chosen for its facilitated flexibility that allows the interviewer to explore specific topics in depth while also providing the freedom to probe and follow up on interesting points that emerge during the conversation (Kvale, 2007). This method is particularly well-suited for understanding the anticipated varying perspectives of silk production workers regarding the use of 3D printing technology, as conducting interviews online is practical given potential geographic and logistical constraints of communicating with targeted participants, which is identified as a key benefit of conducting online interviews by Opdenakker (2006). This approach also ensures that a broad range of participants can be included as the semi-structured format is beneficial to ensure that while there is a consistent framework guiding each interview, there is als opportunity for participants to express their viewpoints and experiences that would lead to richer and more detailed insights (Gill et al., 2008).

### 3.4 Time horizon

This study adopts a cross-sectional time horizon to collect data at a single point in time, capturing the current perceptions and experiences of silk industry professionals in Hangzhou regarding the impacts/ perceived impacts from the application of 3D printing technology.

### 3.5 Sampling strategy

The sampling strategy for this study involves purposive sampling, targeting individuals who have significant experience and knowledge in silk production in Hangzhou, China. Participants will include plant managers, experienced artisans and technical staff involved in silk production practices with knowledge or experience of 3D printing to ensure that the sample is relevant to the research objectives. The sample size will be determined based on data saturation with the aiming for around 10-12 participants to ensure a comprehensive understanding of the phenomenon. Recruitment will be facilitated through the personal networks of the researcher through industry associations and professional networks, ensuring access to knowledgeable and experienced individuals who can provide valuable perspectives on the challenges and opportunities presented by 3D printing technology.

### 3.6 Data analysis

Upon the collection of qualitative data from interviews, key themes are examined in accordance to Neuendorf's (2018) content and thematic analysis guideline, beginning with the familiarisation of data through repeated reading of interview transcripts, followed by the generation of initial codes to signified key features and patterns. After that, the researcher will search for themes by collating related codes into common categories, ensuring accurate representation of the related data in the final write-up. Clarke & Braun's (2017) recommended approach to continuously examine for recurring motifs and divergence within identified themes, codes and key examples is adhered, ensuring that the performed data analysis effectively captures the dynamics of attitudes and perceptions of interviewees.

### 3.7 Ethical considerations

This study will strictly cohere to university ethical protocols and ensures that no physical or psychological harm are inflicted on research participants (interviewees) throughout the study. Participants will be fully informed about the research objectives, procedures and their rights through a participant information form that also states their right to withdraw at any time. Informed consent will be obtained before participation, ensuring voluntary and informed participation for all interviewees. Confidentiality and anonymity will be strictly maintained with all personal identifiers removed from the data and findings, all gathered data in forms of voice and written transcripts will be securely stored and only accessible to the researcher. Ethical approval will be sought from the university prior data collection to ensure compliance with required ethical standards, ensuring the protection of rights and well-being of participants. A link to NTU's ethical guidance for research can be accessed here.

### 3.8 Limitations

Despite the facilitated academic rigour from the chosen research methodological system and tools, this study is subject to several key limitations. Firstly, the use of a cross-sectional time horizon means that it captures perceptions and experiences at a single point in time, which may not reflect changes in attitudes over time which might hinder the accuracy of findings (Asiamah et al., 2021). However, due to apparat time and resource constraints for this study, only a cross-sectional time horizon approach is feasible. Secondly, the reliance on purposive sampling and a relatively small sample size may limit the generalisability of the finding (Rai & Thapa, 2015), as the focus on participants from Hangzhou may not fully represent the diversity of experiences in other silk-producing regions in China. Additionally, conducting interviews online may introduce biases related to technological accessibility and comfort with digital communication according to Carter et al., (2021).

## 4. Results and discussion

This chapter presents the key themes identified from the qualitative data gathered across 11 semi structured online interviews conducted, critically discussing the key findings in relation to research objectives and to testify the validity of hypotheses. This chapter is structured in accordance to the sequential order of interview questions as shown in appendix B.

### 4.1 Modern technologies used in silk production

When investigating the modern technologies currently employed across interviewed silk production factories in Hangzhou, China, eight specific types of technologies were identified as summerised in table 1. The most common technologies are automated machines with all 11 interviewees claiming to have adopted it in their factories, followed by computerised and AI driven tools, 3D printing and digital inventory systems. Notably, the key study focus on 3D printing technology is used by 9 interviewees, indicating significant adoption, the following sections will describe each of the 9 identified modern technologies used in silk production.

Table 1: Modern technologies used in silk production

| Combined technologies | No of interviewees reporting usage |
|---|---|
| **Automated machines (reeling, dyeing, customisation)** | 11 |
| **Computerised and AI-driven tools (looms, CAD, design tools)** | 9 |
| **3D printing** | 9 |
| **Digital inventory systems** | 8 |
| **Robotic arms** | 7 |
| **Virtual reality for design** | 6 |
| **Inspection and quality control systems (digital inspection, colour matching, maintenance software)** | 6 |
| **Sustainable technologies (waterless dyeing, energy-efficient machinery, biodegradable inks, solar panels, recycling systems)** | 5 |

Automated machines are used across all interviewed Chinese silk production plants, streamlining the production process by mechanising reeling, dyeing and customisation activities, as shown in figure 6 (Sinosilk, 2024). Automated reeling machines are found to ensure uniform tension that produces consistent silk quality (Luo et al., 2021), dying systems reduces the manual labour and potential human errors in colouring accuracy, resulting in enhanced customisation with personalised designs that speeds up production and enhance precision (Babu, 2012).

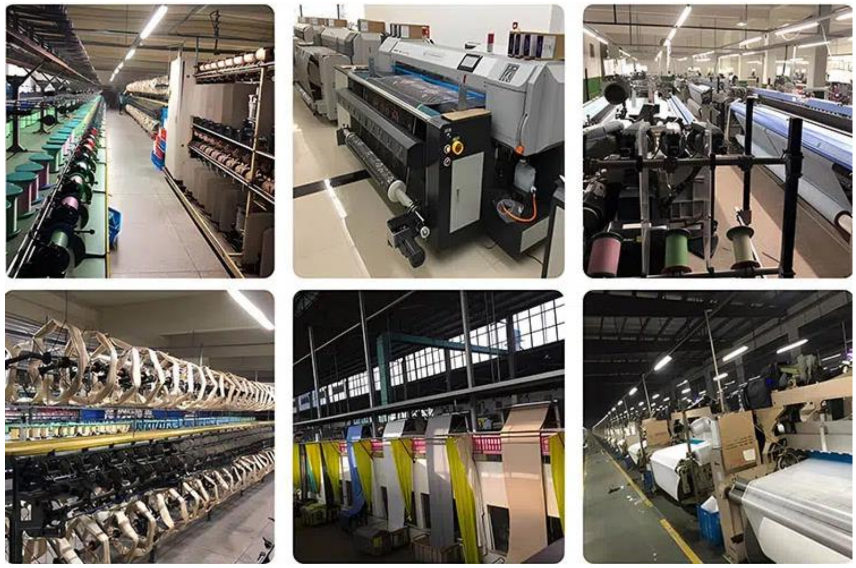

Figure 6: Automated machines used for reeling, dyeing and customisation (Sinosilk, 2024)

The majority (9) of interviewees claimed to use computerised and AI-driven tools, particularly through advanced looming techniques (jacquard, rapier, air-jet, electronic dobby) to provide greater design efficiency and precision for handling the delicate nature of silk weaving whilst maximising the fabric's luxurious qualities in complex designs (Babu, 2020). Additionally, digital design tools like CAD are also widely used in detailed silk design creation and modification (figure 7), combination with AI-driven tools would help to learn from past designs, suggest optimisations and automate traditionally manual design tasks to speed up the design cycle in silk production (Woodbridge, 2024).

Figure 7: Computerised and AI-driven tools (Woodbridge, 2024)

As the main focus of this study, 9 out of 11 interviewees claim to use 3D printing technologies in aiding the creation of complex, customised patterns and structures that were difficult to achieve with traditional methods, providing full control over the entire design and production process as shown in figure 8 to offer unique opportunities for customisation and reducing material waste (Cui et al., 2024).

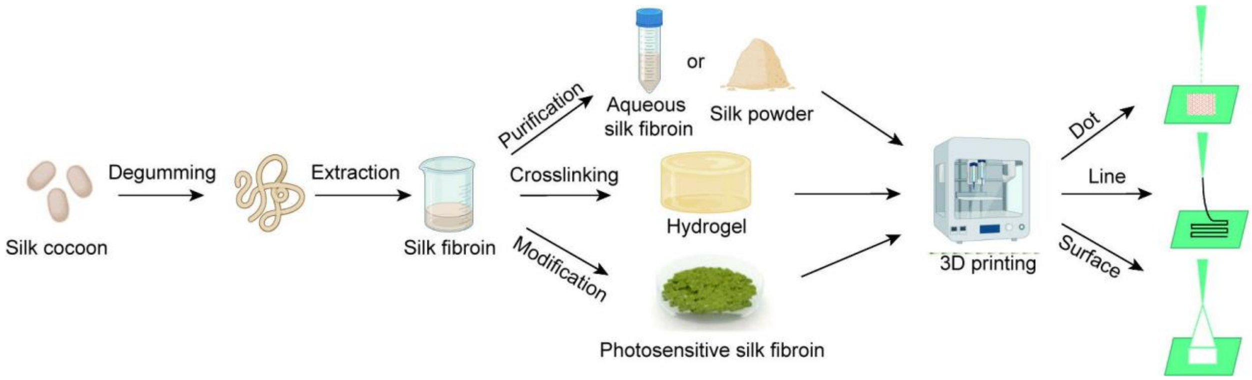


Figure 8: 3D Printing (Cui et al., 2024)

Digital inventory systems are also widely implemented to streamline the management of silk production resources, automating the processes of raw materials tracking, monitoring inventory stock levels and ultimately ensuring the efficient use of resources throughout the production process as elaborated in figure 9 (SCN Soft, 2024). According to Anis et al., (2022), digital inventory systems in textile production helps to reduce waste and optimise production schedules through utilising real-time data for more efficient and responsive decision making.

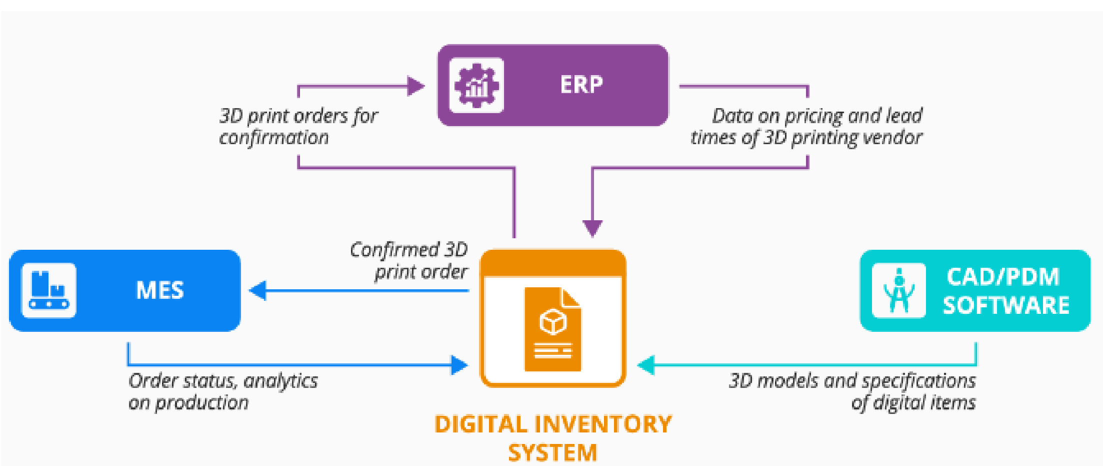


Figure 9: Digital inventory systems (SCN Soft, 2024)

Robotic arms in silk production handle delicate tasks with high precision and reduced human intervention, assisting the design and production processes in threading and weaving to ensure consistent output with minimal fibre damage. Robotically controlled fibre-based silk production exemplifies the convergence of biomimetic digital fabrication and traditional textile processes, enhancing safety levels in the production environment that represents a long-standing concern in traditional silk production due to exposure to boiling water and harmful chemicals (Oxman et al, 2013).

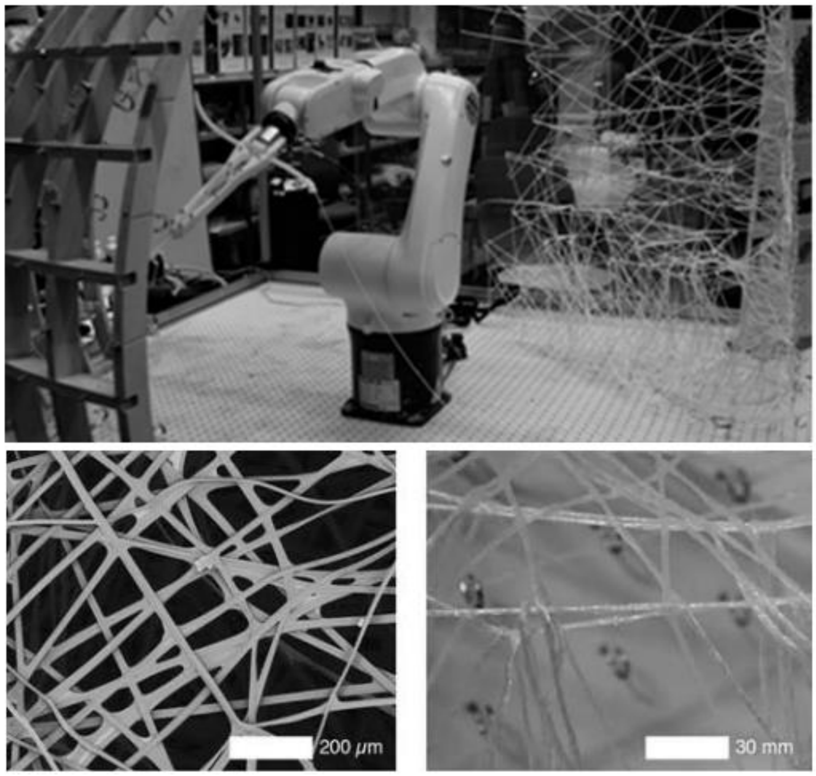


Figure 10: Robotic arms (Oxman et al., 2013)

Virtual reality (VR) for design in silk production allows designers to visualise and modify silk products in a simulated environment, by facilitating the creation of virtual prototypes with capabilities of real-time adjustments, VR designed silk fabric can be produced in an immersive and creativity driven approach, reducing development time and ensuring that final products meet desired specifications before physical production begins, effectively integrating modern innovation with traditional craftsmanship in the design phase (Gokan & Tuschida, 2023).

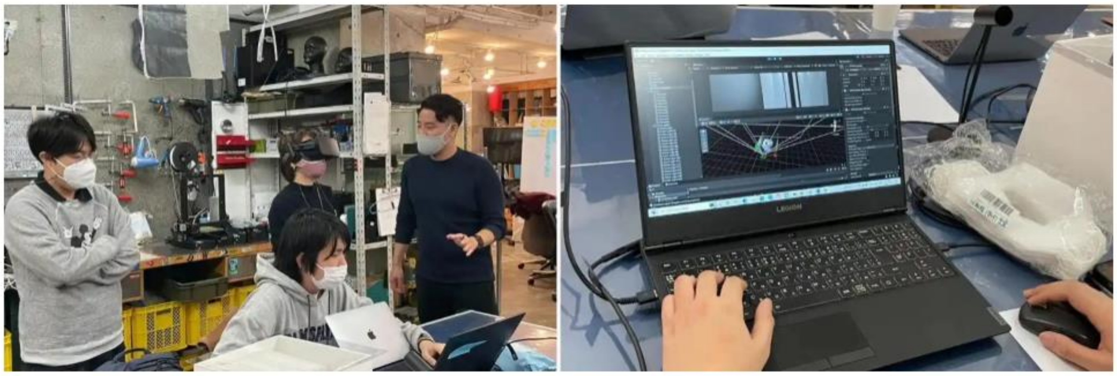

Figure 11: VR for design (Gokan & Tuschida, 2023)

Inspection and quality control systems ensure consistency and high standards in silk production by automatically detecting defects early in the production process to preventing costly errors. Automated colour matching systems guarantee uniformity in dyeing and enhances product quality whilst maintenance software schedules and predicts maintenance needs to minimising downtime and ensuring smooth operation of production machinery (Nath & Dutta, 2023).

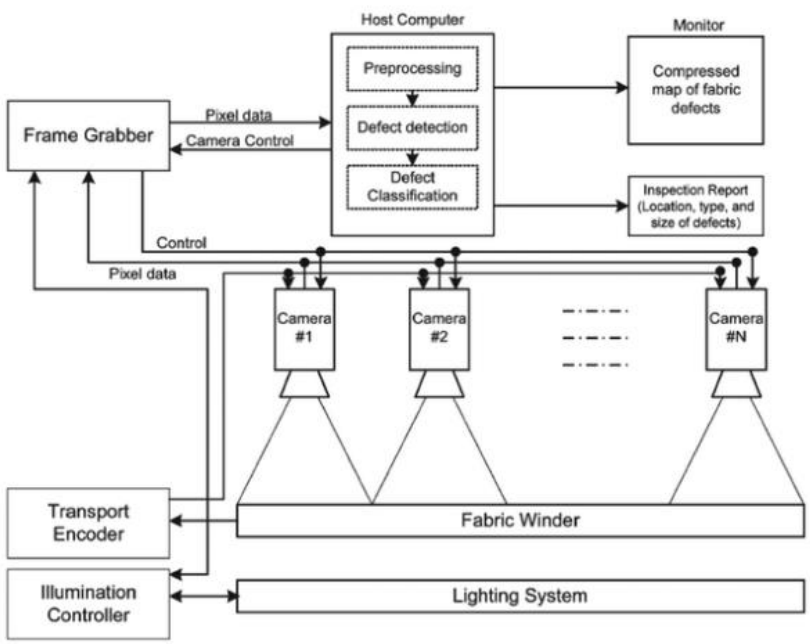


Figure 12: Inspection and digital control systems (Nath & Dutta, 2023)

A range of sustainable technologies are adopted across interviewed silk production plants with the primary focus on reducing environmental impacts, biodegradable silk materials in particular are found contribute to the sustainable decomposition of traditional silk products without harming the environment (Cross, 2022). Other sustainability-oriented technologies include waterless dyeing to conserve water and reduce wastewater pollution, energy-efficient machinery and solar panels are used to reduce energy consumption and provide renewable energy to ensure alignment with China's environmental sustainability goals such as the carbon neutrality goal, peak carbon emissions by 2030 and action plan for water pollution prevention and control (Wang et al., 2021).

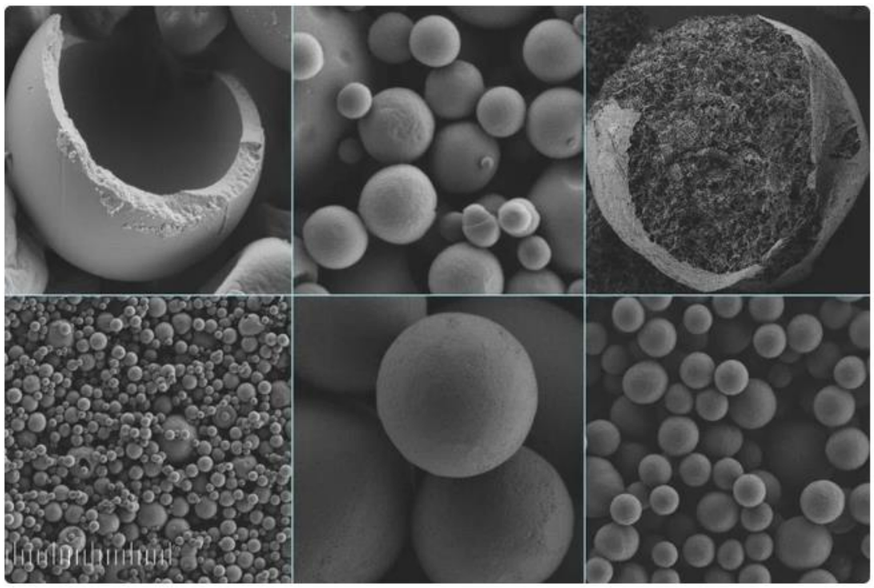

Figure 13: Sustainable biodegradable silk (Cross, 2022)

In the second part of the first question regarding why these modern technologies are adopted in interviewed Chinese silk production plants, several key themes are identified that highlights how technology adoption is driven by efficiency, quality control, innovation, sustainability, cost management, consumer demand and heritage preservation as summerised in appendix C. In the second part of the first question regarding why these modern technologies are adopted in interviewed Chinese silk production plants, several key themes are identified that highlights how technology adoption is driven by efficiency, quality control, innovation, sustainability, cost management, consumer demand and heritage preservation as summerised in appendix C. Central to this is the enhancement of efficiency and productivity as one interviewee noted, "we use automated reeling machines to increase the speed of silk extraction", illustrating the role of automation in expediting processes that traditionally relied on manual labour. Furthermore, the integration of computerised looms and robotic arms are found to enhance precision and reduce the risk of damage to delicate silk threads. The combination of technology and tradition ensures faster production whilst maintaining superior quality control, as highlighted by the use of "advanced sensors to monitor and minimise errors and downtime" amongst interviewees, illustrating fundamental shifts that redefine operational dynamics of the silk production industry in a highly competitive global market.

In terms of innovation and design, the transformative impact of technologies like 3D printing and CAD software is highly significant as they are found to facilitate the creation of intricate patterns and textures that were previously unattainable, allowing for a vibrant intersection of art and technology. One respondent shared, "3D printing allows us to experiment with new textures and patterns", underscoring the enhanced creative capabilities. This innovation is complemented by sustainability efforts including the adoption of waterless dyeing technology and energy-efficient machinery. As noted, "biodegradable inks are used in our printing processes", reflecting a commitment to reducing environmental impact. Moreover, the strategic use of AI-driven design tools and virtual reality pushes beyond traditional creative boundaries in alignment with the rapidly changing consumer demand for developing customised, eco-friendly products. This approach ensures that the industry can meet contemporary challenges while honouring its rich cultural heritage, as seen in the careful integration of modern looms with traditional hand-finishing techniques, balancing old and new that preserves the authenticity of silk production and sets the stage for a sustainable, innovative future.

**4.2 Implementing new technologies in silk production processes**

The second interview question explored whether implementing new technologies in silk production were easy or difficult, resulting an overwhelming consensus over apparent implementation challenges as summerised in appendix D that reaffirms Babu's (2012) claims that implementation new technology in fashion production. Amongst the main themes identified, training and skill development represents a key theme critical challenge considered by silk production workers when implementing new technologies. Many respondents highlighted that "implementing new technologies requires extensive training for our staff", indicating a significant gap between traditional skills and the advanced knowledge required for modern machinery. The need for advance technical know-how is further emphasised by comments such as "there's a steep learning curve associated with adopting new machinery", as the lack of skilled technicians compounds the issue, making continuous education and upskilling imperative yet particularly challenging. One respondent noted, "we invest in continuous education to keep up with technological advancements", this reflects the ongoing effort to bridge the skills gap, underscoring the importance of comprehensive training programmes that equip workers with the necessary skills and foster a culture of continuous learning. Without addressing this, the adoption of new technologies in fashion production may remain limited and inefficient.

Cost and investment present substantial barriers to technological adoption, as highlighted by "the initial investment for new technology is quite high" where high startup capital coupled with significant maintenance and operating costs strain many companies' finances. One interviewee mentioned, "maintenance and operating costs for modern machinery are significant", underscoring the ongoing financial burdens and related costs that often delays technology adoption, with respondents noting, "cost is a major barrier to implementing cutting-edge solutions", positing that securing necessary investment can be difficult which further complicates efforts to implement modern technologies. Additionally, integration with existing systems is fraught with compatibility issues, as indicated that "integrating new technology with our existing systems is often problematic", requiring frequent modifications and careful strategic planning. The natural resistance to change among employees particularly older ones is also found to complicate this transition. Effective leadership and communication are essential to overcoming this resistance, as highlighted that “we need to constantly reassure our employees about the advantages of modernisation”. Lastly, the technical support and maintenance necessary for smooth operation are found to be important yet highly challenging, with reliance on external experts often causing delays. One respondent noted, “we often rely on external experts for technical support”, highlighting the need for robust in-house capabilities to ensure continuous and effective maintenance which might be lacking in silk production plants.

**4.3 Biggest challenges to silk production**

The third interview question investigated the key challenges in modern silk production, aiming to expand upon Mu et al.’s (2020) argument that silk production is traditionally challenged by its labour-intensive characteristics and difficulties in maintaining high quality silkworm ecosystems, several main themes including economic pressures, technological disruption, environmental regulations, labour issues, market demand fluctuations and supply chain disruptions are identified as shown in appendix E. Economic pressures and technological disruption are found to be key threats to silk production today, especially in the recent pandemic and post pandemic recovery period where macro-economic conditions are stagnating and disrupted. Rising labour costs is found to complicate profitability, with one participant noting that “rising labour costs make it difficult to maintain profitability”. The fluctuating price of raw silk adds another layer of financial strain, making cost management more challenging. Additionally, economic downturns reduce consumer spending on luxury items like silk, exacerbating financial instability of companies due to vulnerability to uncontrollable market demand changes. The increasing competitiveness of the global market is found to be highly challenging, as suggested that “global competition drives down prices, squeezing our margins”, Access to affordable financing is increasingly difficult to secure, hindering operational sustainability with inflation and economic instability further compounding these financial challenges, making it increasingly difficult for silk producers to maintain its financial health. Most importantly, technological advances are perceived as a double-edged sword, while they offer innovative solutions the rapid pace of change could outstrip the industry's ability to adapt, risking the loss of traditional skills as new methods are adopted.

Labour issues and market demand fluctuations also pose substantial challenges, whereby the difficulty in finding skilled labour coupled with a generational gap in interest in silk production careers in China represents is a major concern as one respondent observed, “finding skilled labour is increasingly difficult”. Labour shortages are found to disrupt production schedules and retaining experienced workers is a persistent issue. Additionally, one interviewee claimed, “consumer preferences are constantly changing, making it hard to predict demand”, illustrating the rapidly changing preferences of modern Chinese silk consumers that require constant modifications and innovation to satisfy which are costly and difficult to ensure. Production planning and inventory management are found to be increasingly challenged by these unpredictable market fluctuations, as the rise of fast fashion reduces the demand for high-quality silk and the fast-paced nature of changing market trends exacerbates these issues. Moreover, supply chain disruptions driven by geopolitical events are found to cause transportation delays and increasing dependence on international/ major local suppliers which pose significant risks. One respondent highlighted, “supply chain disruptions can halt our production entirely”, illustrating the drastic impact of these disruptions that further complicating the industry's efforts to maintain a stable supply of high-quality raw silk.

## 4.4 3D Printing technology adoption amongst Chinese silk production

The fourth interview question examines the current state of and attitudes toward 3D printing technology adoption and amongst Chinese silk production which remains a relatively unexplored gap despite its recognised qualities and advantages in optimising fashion production (Wang et al., 2019; Zhou et al, 2021). As summerised in appendix F below, major themes relate prominently to the current use and its benefits with a majority of participants (9 out of 11) already adopted 3D technologies to create intricate designs and reduce material waste. One respondent highlighted, “we currently use 3D silk printing to create complex designs that are not possible with traditional methods”, illustrating the enhancement of creative capabilities and precision. 3D Printing technology's ability to “streamline the prototyping process and improve product quality” was also noted, as this high level of adoption reflects a strategic move towards innovation that allows for customisation and high-quality products, meeting specific client requirements and positioning these manufacturers more competitively in the global market.

Despite these benefits, high levels of familiarity of challenges and barriers to adopting 3D silk printing remain significant as many respondents cited the high costs of technology as a primary barrier, with one stating that “the cost of 3D silk printing technology is a significant barrier for us”. Similarly, concerns about technical integration and the steep learning curve have refrained adoption among two interviewees, stating that "our existing machinery may not be compatible with 3D printing technology". Moreover, a knowledge gap exists where familiarity with the concept does not translate into detailed understanding or readiness to implement, as one interviewee pointed out, “I have heard of 3D silk printing, but I am not very familiar with the technical details”, highlighting an apparent technical knowledge gap that underscores the need for educational sessions and technical support. Nevertheless, there is an overall strong potential for innovation and sustainability considerations, as many respondents believe that 3D silk printing could revolutionise design capabilities and align with sustainability goals claiming that "we are evaluating 3D silk printing for its environmental benefits." These insights indicate a cautious yet generally optimistic outlook towards future adoption of 3D printing amongst silk production, especially when cost, knowledge and integration challenges can be effectively resolved.

## 4.5 Key benefits of 3D printing in Chinese silk production

The fifth interview question extracts several recognised benefits of 3D printing technologies from literature including enhanced functionality of silk fabrics (Zhou et al., 2018), increased perceived usefulness (Wang et al., 2019), efficiency gains (Denuwara et al., 2019) and reduced environment impacts (Nayak et al., 2022), examining whether they are highly perceived in comparison to traditional Chinese silk production methods. The identified key themes as summerised in appendix G demonstrates that the adoption of 3D silk printing technology significantly enhances the functionality of silk fabrics, offering unprecedented capabilities and applications. Respondents highlighted that “3D silk printing allows us to create fabrics with unique textures and properties”, highlighting its transformative potential to overcome traditional silk production limitations from manual efforts. The ability to incorporate advanced functionalities such as water resistance, customised stretch and strength characteristics also demonstrates how 3D printing expands the practical applications of silk. One interviewee noted, “we can produce silk with embedded sensors and smart features”, highlighting the innovative possibilities for technical textile functionality making it more suitable for diverse applications, leveraging its facilitated precision and highly versatile material characteristics in functional enhancements compared to traditional methods.

Moreover, 3D silk printing is perceived to boost efficiency and reduce environmental impact, making it an attractive technology for modern silk production from a stakeholder perspective. The reduction in material waste and the lower use of water and chemicals compared to traditional dyeing methods are significant environmental benefits. As one respondent remarked, “3D printing reduces material waste significantly”, aligning well with sustainability goals set out by the Chinese government, supporting eco-friendly practices and further reducing the industry's carbon footprint. On the efficiency front, 3D printing streamlines production workflows as noted that “we can produce complex patterns faster with 3D printing”, eliminating areas of inefficient and extensive manual labour that enhances overall production efficiency and improves turnaround times for new complex production designs. However, challenges such as the high initial costs and the need for significant maintenance and technical support are again discussed. Despite these barriers, 3D printing offers a competitive edge in the market, attracting niche customers and enhancing brand image through innovative, bespoke silk products. This market differentiation, combined with the functional and environmental advantages highlights the transformative impact of 3D silk printing technology adoption in comparison to traditional silk production.

In consideration of the identified key themes, the opportunities-based hypothesis as aforementioned in section 2.5 is found to be strongly supported by the gathered qualitative findings. Interviewees consistently reported that 3D printing technology enhances the functionality of silk fabrics, allowing for unique textures and advanced features like embedded sensors. The perceived usefulness is heightened by the technology’s ability to meet specific needs and improve product quality, whilst efficiency gains are evident through reduced manual labour and faster production times. Moreover, environmental impacts are mitigated by significantly lowering material waste and reducing water and chemical usage, aligning with key sustainability goals.

## 4.6 Key challenges of 3D printing in Chinese silk production

The sixth interview question extracts several recognised challenges of 3D printing technologies from literature including high start-up and maintenance costs, lack of technical expertise ((Babu, 2012), perceived difficulty of use (Qin & Xiaoming, 2022) and potential loss of traditional cultural values (Zanier, 2020), examining whether they are highly perceived in comparison to traditional Chinese silk production methods. The identified key themes as summerised in appendix H demonstrates that the adoption of 3D silk printing technology poses apparent challenges that could hinder the adoption or the effective use the technology in silk production. The high start-up and maintenance costs associated with 3D silk printing technology are again repeatedly discussed as significant barriers to its adoption, with respondents highlighting the prohibitive initial investment and ongoing operational expenses as major concerns as stated “the initial investment for 3D printing technology is prohibitively high”. Additionally, maintenance costs for advanced machinery add to the economic burden making it challenging for many smaller-sized or lesser financially healthy companies to justify the transition/ implementation of 3D printing technologies. The complexity of the technology further compounds these issues, requiring specialised knowledge and skilled technicians who are often in short supply as one interviewee mentioned, "we lack the technical know-how to integrate 3D printing into our processes", highlighting the critical gap in technical expertise within existing workforce that requires external support. Training staff is another hurdle with the steep learning curve and the perceived difficulty of use deterring potential adopters, claiming that "3D printing is seen as complicated and difficult to operate" due to its apparent technological and operational challenges.

The concerns about the potential loss of traditional cultural values also hinder the adoption of 3D silk printing, as respondents expressed fears that modern technology might replace traditional silk-making techniques and diminish the cultural heritage associated with silk production. One interviewee claimed, "there is a fear that 3D printing could erode traditional silk-making techniques", indicating clear resistance to change due to cultural preservation concerns. This sentiment is also echoed by those who worry that adopting modern methods could undermine the authenticity and artisanal value of silk products. Additionally, market acceptance and consumer perception pose significant challenges as there is apparent scepticism about the quality and authenticity of 3D printed silk, with respondents noting that "consumers might not value 3D printed silk as highly as traditionally made products". Furthermore, the complexity of effectively integrating with existing production processes is again discussed, requiring significant adjustments and careful management to avoid disruptions. "Integrating 3D printing with our current production methods is complex", as one participant pointed to the operational challenges of merging traditional techniques with new technology. These multifaceted barriers necessitate a balanced approach that addresses a diverse combination of financial, technical, cultural and market-related concerns to facilitate the successful adoption of 3D printing in the Chinese silk industry.

In consideration of the identified key themes, the challenges-based hypothesis is found to be partially supported by the gathered qualitative findings. Interviewees noted that high start-up and maintenance costs present significant financial barriers to adopting 3D printing technology. The lack of technical know-how and expertise further complicates integration with many respondents highlighting the steep learning curve and complexity of the technology. Additionally, the perceived difficulty of use and potential loss of traditional cultural values hinder widespread adoption, as these concerns foster resistance among traditionalists. However, while these barriers are substantial, they do not completely prevent the adoption of 3D printing, suggesting that with appropriate strategies and support that these challenges can be effectively mitigated.

### 4.7 Balancing traditional and new technologies to preserve cultural heritage in silk production

The final interview question attempted to address the identified research gap where inadequate studies have been conducted on exploring how traditional and new technologies can be balanced to preserve cultural heritage in silk production, which represents a critical challenge when integrating new technologies in traditional fashion production (Qin & Xiaoming, 2022). The identified key themes as summerised in appendix I demonstrates that the balancing of traditional techniques with new technologies in silk production can be achieved through integration and selective use. Respondents highlighted that modern tools are used to enhance and not replace traditional methods, for instance one interviewee claimed that "we use modern looms but ensure the final hand-finishing is done traditionally”, illustrating a collaborative process where technology aids efficiency while preserving artisanal quality. Another example is where while laser cutting provides precision, the need for hand assembly maintains a certain degree of crafts heritage and demonstrates how digital and manual methods coexist. Under the theme of selective adoption of technology, the implementation of 3D printing technologies is in general recognised as supportive rather than overshadowing traditional craftsmanship with the essence of heritage techniques preserved. One participant noted, “we evaluate each new technology for its impact on cultural heritage before adoption”, indicating a strategic approach to integrating innovations, utilising the perceived benefits of technology like precision and efficiency, while keeping traditional silk-making's cultural and artistic value intact.

The theme of training and education is found to play an important role in preserving cultural heritage while embracing modern advancements, “we train our staff in both modern technologies and traditional methods”, to ensure comprehensive skill set via a dual focus of implemented training/ educational programmes. In several interviewed silk production plants, workshops on heritage techniques are mandatory for new employees that emphasises the importance of traditional skills should the implemented technologies fail to operate or maximum automated production capacity is reached where manual labour is required. Additionally, involving artisans in the decision-making process for adopting new technologies helps maintain authenticity, as another interviewee shared “we collaborate with traditional artisans to ensure their skills are preserved”. This collaborative approach ensures that technological advancements are adapted to fit within the framework of traditional processes, fostering innovation within the boundaries of cultural heritage by promoting cultural significance through activities including storytelling and customer engagement, silk manufacturers can raise awareness about the importance of heritage in silk production that effectively balances innovation with respect for preserving its cultural roots.

## 5. Conclusion

This study critically analysed the opportunities and challenges of applying 3D printing technology in traditional Chinese silk-making, aiming to fill a gap in current literature which predominantly focuses on the application of 3D printing in fields like biomedical engineering (Wang et al., 2019; Zhou et al., 2021; Zhang et al., 2021). The research objectives examined the adoption of modern technologies in silk production, evaluating the benefits and environmental benefits of 3D printing, investigating adoption barriers and exploring the balance between traditional and modern techniques in silk making, contributing with new insights to the adoption of new technologies in traditional fashion production.

Research findings revealed extensive and a vast range of adoption of modern technologies in silk production, aligning with findings by Luo et al. (2021) and Babu (2012), who emphasised the efficiency and quality improvements brought by automation and computerised tools. The identification of eight specific technologies included automated machines, computerised and AI-driven tools, 3D printing, digital inventory systems, robotics, VR, inspection and quality control systems, and sustainable technologies, highlighting a significant technological shift within the Chinese silk production industry. These findings support current literature knowledge and reaffirms the transformative impact of digital tools in enhancing production efficiency and precision, but this study extends on literature by providing a detailed account of the specific modern technologies currently applied in the context of traditional Chinese silk production, offering a focused analysis that has not previously explored in depth.

Amongst the identified technologies, 3D printing technology has emerged as a key transformative tool which helps to enhance the functionality and customisation capabilities of silk fabrics, supporting the assertions by Cui et al. (2024) and Denuwara et al. (2019) regarding the potential of 3D printing to create complex designs and reduce material waste. The production of complex patterns and structures by 3D printing is found to offer unprecedented customisation opportunities, whereby its environmental benefits such as reducing material waste and minimising the use of water and chemicals are found to overcome key challenges of traditional silk production as discussed by Nayak et al. (2022). This study contributed with new insights by contextualising these benefits within traditional Chinese silk-making, demonstrating that 3D printing can support sustainability goals while enhancing production efficiency.

Alternatively, the adoption of 3D printing technology also faces significant barriers such as high startup, maintenance costs and a lack of technical expertise, corroborating with the findings of Babu (2012) and Qin & Xiaoming (2022) who noted similar financial and technical hurdles in other fashion production industries. The steep learning curve and perceived complexity of 3D printing are found to deter wider adoption, emphasising the need for substantial investment in continuous training and technical support. This study adds to the literature by highlighting the specific cultural preservation concerns in the silk industry, where there is a fear that modern technologies might replace traditional techniques and diminish the cultural heritage of silk production, given that this aspect has been relatively underexplored in existing studies, this research represents a valuable contribution to understanding the balance between innovation and cultural preservation in fashion production.

The successful integration of modern technologies with traditional methods in silk production was achieved through selective adoption and collaboration with traditional artisans. Training programmes that equip workers with skills in both modern and traditional techniques are essential for maintaining authenticity, a finding that aligns with Woodbridge (2024). This combined focus ensures that modern tools enhance efficiency without overshadowing the artisanal value of traditional silk-making. The promotion of cultural significance through storytelling and customer engagement also reflects a strategic approach to integrating innovations while respecting heritage, adding a new dimension to the existing literature on technology adoption in traditional crafts.

The study's hypotheses were tested and found to be supported. The opportunities-based hypothesis was strongly supported, with 3D printing technology enhancing the functionality, perceived usefulness, efficiency and environmental sustainability of silk production. The challenges-based hypothesis was partially supported, although significant barriers were identified, they do not entirely prevent the adoption of 3D printing technology given the implementation of strategies and support that can mitigate these challenges, providing a pathway for successful integration. In terms of research gap contribution, this study provides a comprehensive analysis of how modern and traditional silk production methods can be balanced to preserve cultural heritage while leveraging technological advancements, offering new perspectives on the specific application of 3D printing in the Chinese silk fashion industry, contributing to the sustainable development and cultural preservation of the industry. These insights can contribute to industry stakeholders seeking to innovate while maintaining the rich cultural legacy of traditional silk-making, thus filling a critical gap in the existing literature.

### 5.1 Limitations and implications for future studies

While this successfully fulfilled all proposed research objectives, several limitations were apparent that can be addressed in future studies. To begin with, the sample size was confined to professionals from silk production factories in Hangzhou, China given it being the primary silk production hub in China. However, future studies can broaden the geographic scope to include additional regions with significant silk production could yield a more diverse and comprehensive understanding, especially in lesser developed Chinese cities where funds for investments in new technologies are limited. Moreover, the study primarily focused on 3D printing technology, potentially overlooking other emerging technologies in silk production that warrant further exploration. The reliance on qualitative data introduces the possibility of biases linked to personal interpretations of the interviewees.

Notwithstanding these limitations, the findings present several implications for future research. Incorporating quantitative methods in subsequent studies could validate and extend the qualitative findings, offering a more robust analysis of the impacts of 3D printing and other technologies. Longitudinal studies would be valuable in assessing the long-term effects of integrating 3D printing technology on silk production efficiency, sustainability, and cultural preservation. Additionally, exploring the interaction between various modern technologies and traditional techniques in silk production across different cultural contexts would enhance understanding of their potential to coexist and complement each other. Further research should also investigate the socio-economic impacts of technological adoption on the workforce within the silk industry. This could provide critical insights into addressing the skills gap and promoting inclusive growth. By addressing these areas, future research can build upon the insights provided by this study, contributing to the sustainable and culturally respectful evolution of the traditional silk-making industry.

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